Cascading Failure Risk Estimation and Decentralized Mitigation

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Abstract

We propose a new method to estimate the risk of large cascading blackouts triggered by multiple contingencies, using a search algorithm called "Random Chemistry". Risk estimates converge at least two orders of magnitude faster than a conventional Monte-Carlo simulation for two test systems (e.g., Fig. 1). Using this method, we can quickly estimate how risk changes with load level (Fig. 2) and find the most critical components in a power grid (Fig. 3). We further propose a decentralized overload mitigation approach to stop a potential cascade (Fig. 4).

Estimating Cascading Failure Risk

A standard measure of risk due to a random disturbance:

$$R(x) = \sum_{\forall c \in \Omega} \Pr(c) S(c,x)$$

Monte-Carlo:

$$\hat{R}_{MC}(x) = \frac{1}{|\Omega_a|} \sum_{c \in \Omega_a} S(c,x)$$

Random Chemistry:

$$\hat{R}_{RC,k}(x) = \frac{m_k}{|\Omega_{RC,k}|} \sum_{d \in \Omega_{RC,k}} S(d,x) \left(\prod_{i \in d} p_i \right)$$

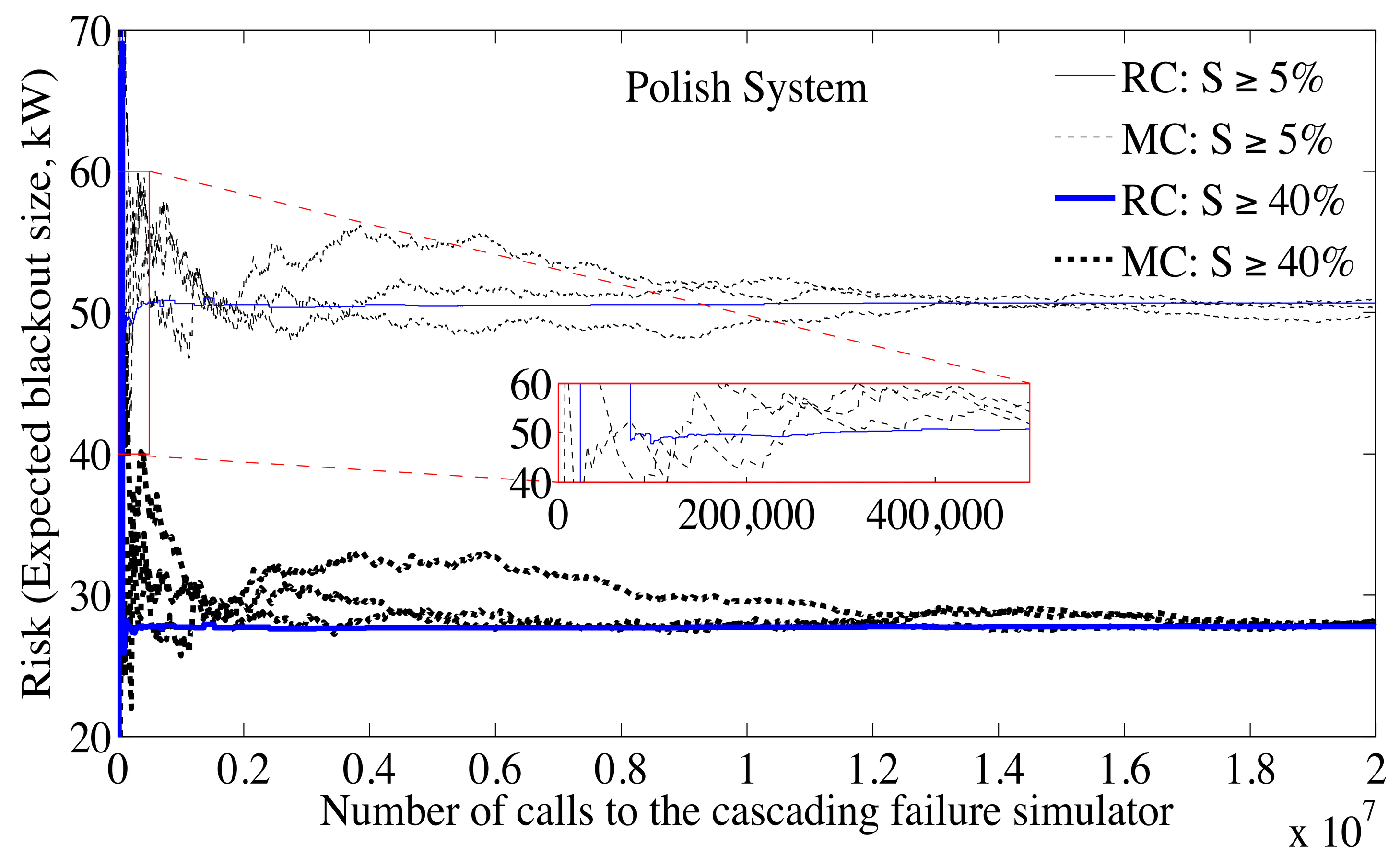

Figure 1. Cascading failure risk estimates using the Random Chemistry and Monte-Carlo methods in the Polish grid with 2896 branches.

Risk as a function of load

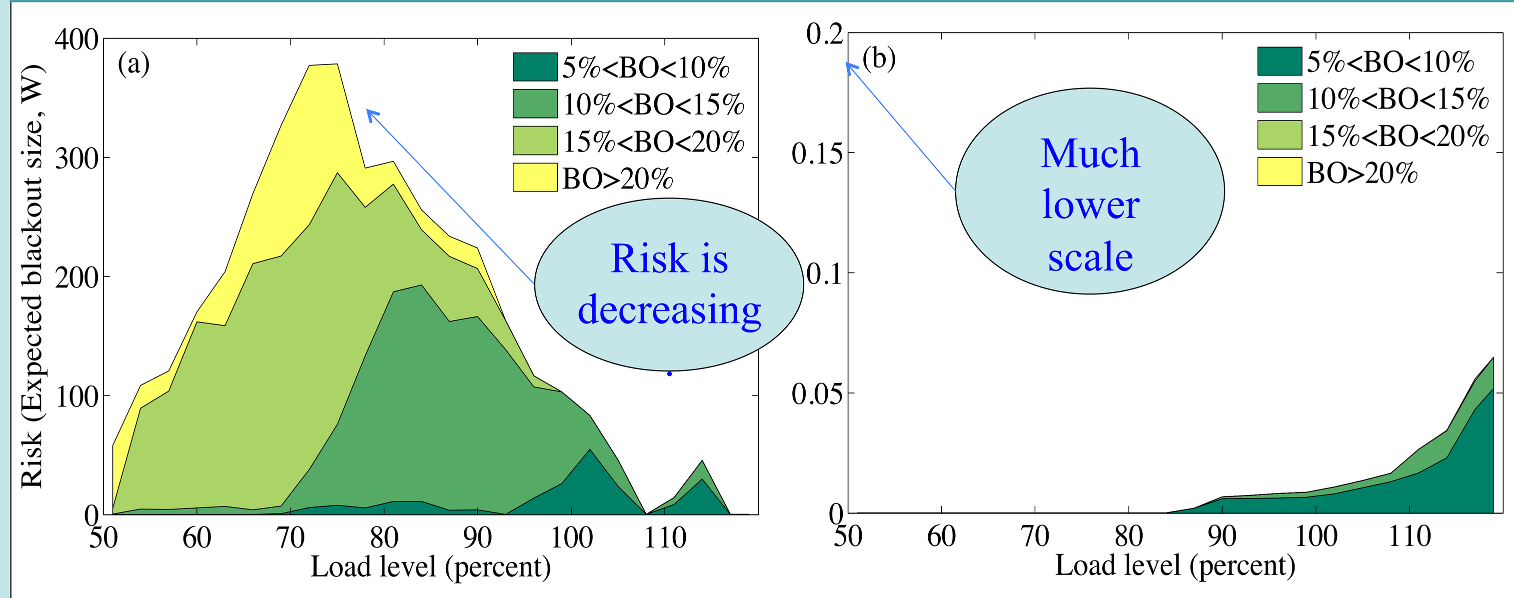

Figure 2. Cascading failure risk vs. load level for RTS-96: (a) SCDCOPF, and (b) Proportional dispatch. The proportional dispatch is more expensive, but has a much lower risk, which shows a trade-off between cost of dispatch and risk.

Sensitivity of Risk to individual branch outage probabilities

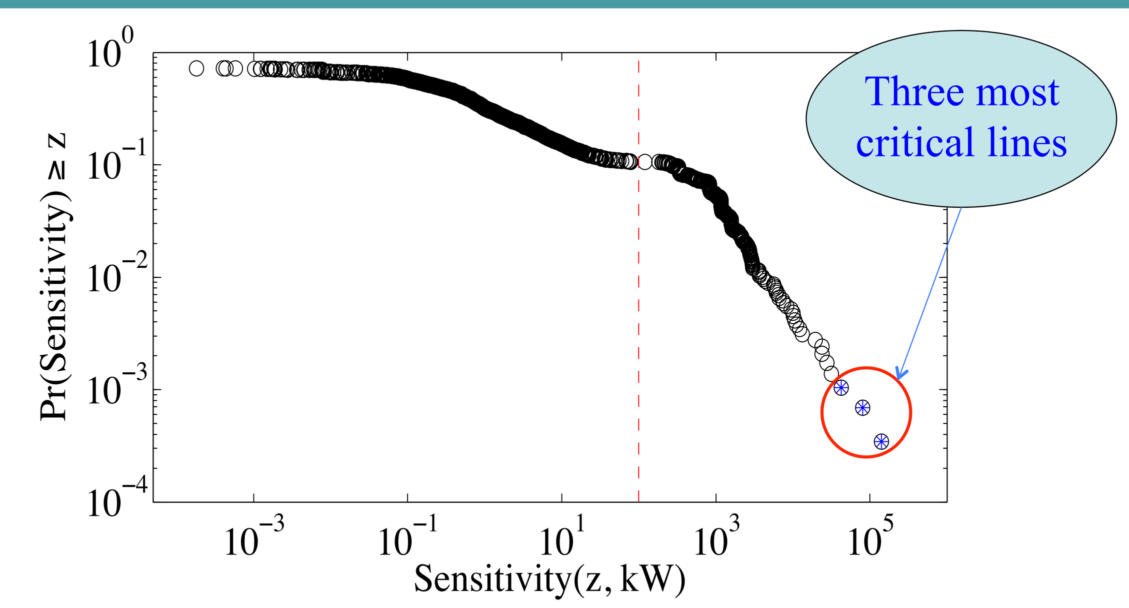

Figure 3. Complementary Cumulative Distribution Function of sensitivities (one circle per branch)

$$\frac{\partial \hat{R}_{RC,k}(x)}{\partial p_i} = \frac{m_k}{|\Omega_{RC,k}|} \sum_{d \in \Omega_{RC,k}} S(d,x) \left(\frac{\partial \Pr(d)}{\partial p_i} \right)$$

Disadvantages of Centralized Control

A central controller has certain flaws when it comes to implementation, which makes it impractical:

- It needs a huge communication infrastructure to collect and submit information to the whole network
- It is more vulnerable to failures. One failure in a part of the system can collapse the control scheme.
- There are multiple control regions in an actual large-scale power grid, with operators each being in charge of their own area.
- <u>Variation in load/generation on a bus typically has localized effects and does not generally affect the whole system.</u>

Decentralized Overload Mitigation Problem

$$\begin{aligned}
\underset{\Delta \mathbf{P}_{D,\Omega}, \Delta \mathbf{P}_{G,\Omega}}{\text{Minimize}} \quad & -\mathbf{1}^T \Delta \mathbf{P}_{D,\Omega} + \mathbf{\Lambda}^T \mathbf{f}_{\text{over},\Omega} \\
\text{subject to} \quad & \Delta \mathbf{f} = \mathbf{X}_b^{-1} \mathbf{A}^T \Delta \boldsymbol{\theta} \\
& -\mathbf{f}_{\max,\Omega} - \mathbf{f}_{\text{over},\Omega} \le \mathbf{f}_{0,\Omega} + \Delta \mathbf{f}_\Omega \le \mathbf{f}_{\max,\Omega} + \mathbf{f}_{\text{over},\Omega} \\
& \mathbf{B} \Delta \boldsymbol{\theta} = \mathbf{A}_G \Delta \mathbf{P}_G - \mathbf{A}_D \Delta \mathbf{P}_D \\
& -(\mathbf{P}_{G0,\Omega} - \mathbf{P}_{G,\min,\Omega}) \le \Delta \mathbf{P}_{G,\Omega} \le 0 \\
& -\mathbf{P}_{D0,\Omega} \le \Delta \mathbf{P}_{D,\Omega} \le 0 \\
& \Delta \mathbf{P}_{G,\Omega^c} = 0 \\
& \Delta \mathbf{P}_{D,\Omega^c} = 0 \\
& \mathbf{f}_{\text{over},\Omega} \ge 0
\end{aligned}$$

Ω: node/line local neighborhood, Ω^c: nodes outside Ω

$\Delta\mathbf{P}_D/\Delta\mathbf{P}_G$: variation in load/generation

$\mathbf{f}_{\text{over}}$: slack variable to define a soft constraint for overload

B: bus susceptance matrix

After each agent solves their own optimization problem with the optimization control variables to exist only in the local neighborhood, it implements the load/generation reduction only on its own when negotiation is off, or the whole local neighborhood when negotiation is on.

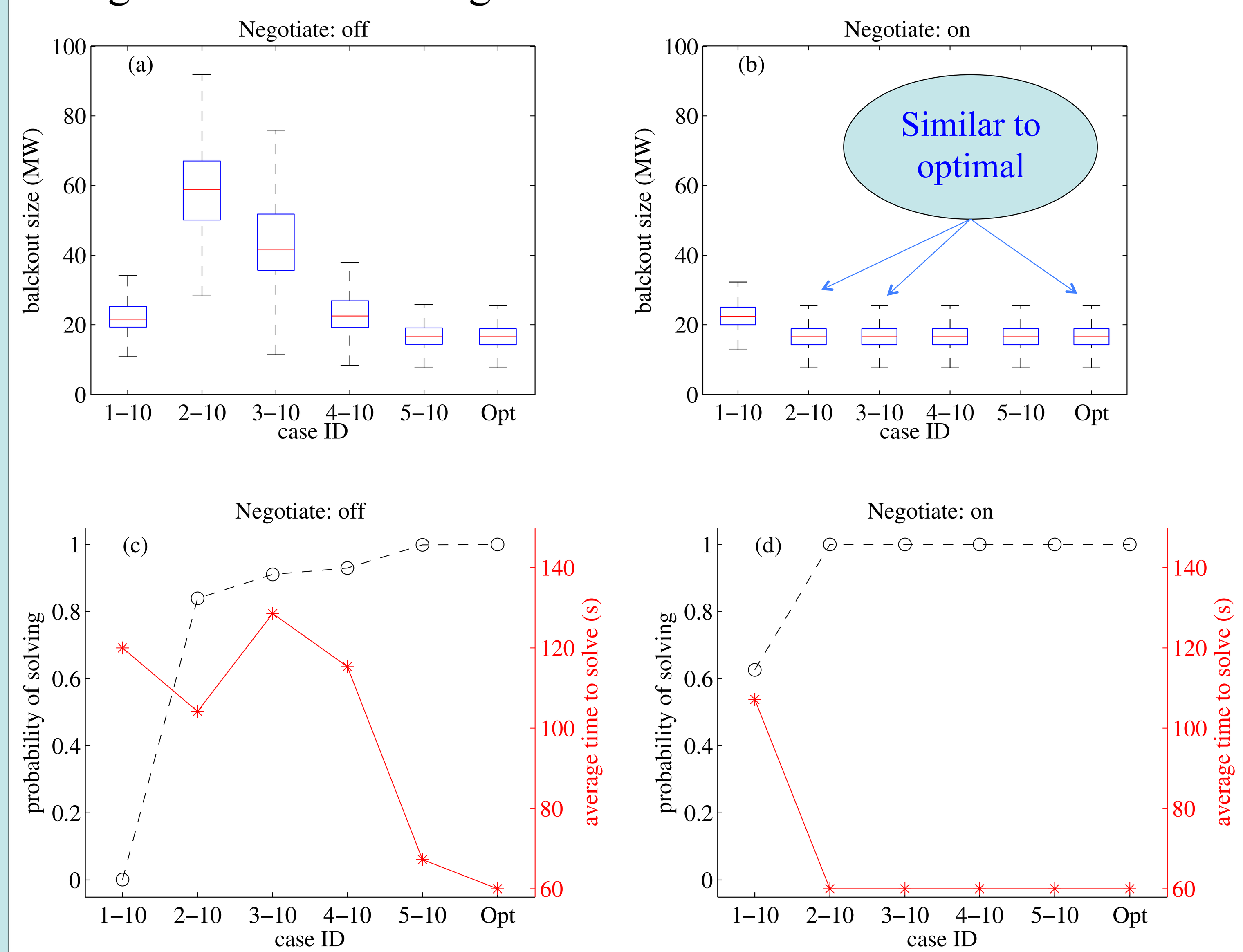

Figure 4. Statistical performance of the decentralized controller after applying all n-2 contingencies to a modified IEEE 30-bus case: The box plot indicates total blackout sizes, where the line shows the median value (a) without, and (b) with negotiation capability; bottom panels show empirical probability of eliminating overloads (dashed line and circle markers) and the average time (solid line and asterisk markers) that it takes to solve the problem (c) without, and (d) with negotiation. The case ID p-q represents the local neighborhood size p and extended neighborhood size q.